THERMAL-INFRARED IMAGER TIR ON HAYABUSA2 FOR OBSEVATION OF ASTEROID (162173) 1999JU3. T. Okada[1,10], T. Fukuhara[3], S. Tanaka[1,2,10] , M. Taguchi[4], T. Imamura[1,10], T. Arai[2], H. Senshu[5], Y. Ogawa[6], H. Demura[6], K. Kitazato[6], R. Nakamura[7], T. Kouyama[7], T. Sekiguchi[8], S. Hasegawa[1,2], T. Matsunaga[9], T. Wada[1], J. Takita[1,10], N. Sakatani[1,11], Y. Horikawa[1,11], S. Kuwano[6], J. Helbert[12], T. Mueller[13], A. Hagermann[14], and Hayabusa2 Thermal-Infrared Imager (TIR) Team[2], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA) (3-1-1 Yoshinodai, Chuo-Ku, Sagamihara 252-5210, Japan, okada@planeta.sci.isas.jaxa.jp), [2]JAXA Space Exploration Center, Japan Aerospace Exploration Agency (JSPEC/JAXA), Sagamihara, Japan, [3]Hokkaido University, Japan, [4]Rikkyo University, Tokyo, [5]PERC, Chiba Institute of Technology, Japan, [6]CAIST, University of Aizu, Japan, [7]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan, [8]Hokkaido University of Education, Asahikawa, Japan, [9]National Institute of Environmental Studies (NIES), Tsukuba, Japan, [10]University of Tokyo, Japan, [11]Graduate University for Advanced Studies (Sokendai), Japan, [12]Institute of Planetary Research, German Space Research Center (DLR), Berlin, [13]Max-Planck Institute for Extraterrestrial Physics, Garching, Germany, [14]The Open University, UK.

Introduction: We have developed and calilbrated Thermal Infrared Imager TIR for investigating thermo-physical properties of C-class near-Earth sub-km sized asteroid (162173) 1999JU3 in Hayabusa2 mission. TIR shows its performance as good as expected during the in-flight test after launch. We summarize development, pre-flight calibration, and in-flight performance of TIR, as well as its future observation plan.

Hayabusa2: Hayabusa2 is the second sample return mission from near-earth asteroid organized by Japan Aerospace Exploration Agency (JAXA) [1]. The mission is the successor of Hayabusa which retrieved samples from the surface of S-class (stony type) near-Earth asteroid 25134 Itokawa [2], and will visit C-class (carbonaceous type) asteroid 1999JU3 and recover the sample from there to Earth. Hayabusa2 was launched by the 26th H2A launch vehicle from Tanegashima Space Center (TNSC) of JAXA on 3 December 2014. The spacecraft will change its trajectory with gravity assist during Earth swing-by in December 2015 and rendezvous the target asteroid in July 2018. Hayabusa2 will observe the asteroid shape, gravity, thermal and physical properties, and mineralogy from the Home Position (HP), 20 km sunward from asteroid surface. It will deploy the European surface robotic lander (MASCOT) [3] and three small rovers for conducting *in situ* surface experiments. In this mission, the asteroid surface will be excavated using the Small Carry-on Impactor (SCI). And Hayabusa2 will collect sample from three different sites on the asteroid by touch and away method. After a 1.5 year-long rendezvous phase, the spacecraft will depart from the asteroid and return to the Earth for sample recovery using the Reentry Capsule.

Thermal and Thermo-physical Measurements in Hayabusa2: In Hayabusa2, thermo-physical studies are planned by TIR from HP, by radiometer (MARA) on MASCOT, and temperature sensors of rovers on the surface of asteroid. TIR images thermal radiation off the asteroid from the Earth direction, complementary to MARA which measures surface radiation day and night on the surface. In the past asteroid and comet missions, thermo-physical properties have not well investigated, although the geological variation in thermo-pysical properties should be as significant as in mineralogical or chemical properties for primitive bodies, since it is assumed an loosely-bound rubble-pile and its surface is considered as fluffy and less dense (more porous) than that of S-class asteroid. Scientific targets and objectives have been introduced by Okada et al. (2014) [4].

Development of TIR: The thermal infrared imager TIR consistes of TIR-S (sensor head) and TIR-AE (power supply). TIR-S includes a micro-bolometer array package (NEC 320A) as detector, a germanium lens based optics, a signal processing circuit, a command and telemetry interface circuit, a thermoelectric cooling system controller and driver circuit, a shutter mechanism and driver circuit. A cone shaped sunshade to avoid direct irradiation of sun light and the reflection from ground is also a part of TIR-S. TIR-AE includes an interface circuit for unregulated 50V bus voltage and a DC/DC converter. The same design is adopted for TIR-S and TIR-AE as LIR [5] onboard Akatsuki (Planet-C) Venus cilmate orbiter to be developed in a very short term. Characteristic performance of TIR is shown in Table 1.

Image storage and processing system in the DE (Digital Dlectronics) is also a part of TIR system [6]. It includes a pre-image buffer, a temporary data storage buffer, a software buffer, and the image processor which has software-based functions such as summation, subtraction, bit-shift, averaging, regional selection, and lossless and lossy data compression for each image taken by TIR. DE also stores the onboard flat pattern noise (OFPN) data in its FLASH memory. Pre-image buffer has a function of fast summation of continuously readout image from TIR at 60 frames per second. The onboard programs are installed in DE for automatic imaging operation and subsequent image processing for TIR.

Calibration of TIR: Function and performance of TIR has been tested and calibrated before its delivery to Hayabusa2 final integration test. Test apparatuses were prepared for those purposes: (1) a cold target apparatus (-40 to 25 °C) using a vacuum chamber, (2) a hot target apparatus (25 to 125 °C) using an oil-bath, (3) a hot target apparatus (25 to 150 °C) using a cavity blackbody (ACE BF-D52-180), (4) a geometrical correction apparatus (<20 to 125 °C) using a collimator (IR System METS L-10-2.9), and (5) other setups. All these apparatuses were calibrated each other using the same devices. In addition, TIR observed thermal IR panel just in front of TIR during the system thermal vacuum test of spacecraft, which varied -120 to 80 °C, and we had an opportunity to take TIR images at -110 and -95 °C). TIR has been proven to image from -100 to +150 °C using a single parameter setting. This fact is important because TIR will be able to image the whole surface of asteoid 1999JU3: not only the sunlit surface but even the night side surface as well. Dawn-dusk areas are so sensitive to determine thermophysical properties such as thermal inertia.

Geometrical calibration was also conducted using the collimater apparatus as well as imaging geometrical structures in the satellite testing room at more than 20 m distance. We determined the field of view as 16.7° x 12.7° for 328 x 248 effective pixels, the spatial resolution as 0.051° per pixel, and the image distortion as almost negligible. The point spread function was investigated using a pin-hole beam and found that it is almost the same as or a little bit less than a single pixel size. This indicates that TIR could find small craters or geological features as small as pixel size, especially to find the crater excavated by impact of SCI.

In-Flight Observation of TIR: After launch, we have tested the functionality and performance of TIR during the initial checkout period in December 2014. TIR imaged the deep space backgrounds as well as the closed shutter for reference, whose surface temperature is monitored. TIR needs temperature control within a narrow range to take image in a desirable performance. A minute temperature control by use of thermal control system of spacecraft will keep the temperatures at TIR optics and at TIR mounting panel within 0.5 °C, which could keep the temperature of the bolometer package and sensor package mounting case within 0.1 °C.

We found TIR performance is as good as tested in the pre-flight test. A long-term trend of degradation will be measured during the 3.5 year-long cruising phase before arriving the target asteroid. We also continue searching for the better setting of temperature control to improve the accuracy of thermal measurements of asteroid.

Future Observation Plan: During the cruise, TIR will image the deep space once every month in order to check its performance in a long-term range, as well as to search the best condition by changing the temperature control. Just before Earth swing by in December 2015, Earth and Moon will be imaged by TIR. During the approach phase, 2000 to 20 km away from asteroid, TIR will observe the light curve profiles, 40 or more images in asteroid rotation (7.6 hours) at several distances from asteroid. After arrival, Hayabusa2 will stay at HP, from where TIR will take 40 or more images durging one asteroid rotation once a week. Hayabusa2 is basically in the Earth direction, from 0° to 40° of Sun-Asteroid-Spacecraft angle. The position will be changed at higher angles to map the whole asteroid. Hayabusa2 will descend to the lower altitude for precise imaging to confirm the touchdown site selection, for deploying the surface lander and rovers, for deploying the SCI impactor, and for collecting samples. TIR will image the surface at higher spatial resolution, e.g., 1 m at 1km altitude. Just before the touchdown, TIR continues imaging down to 5 m altitude.

Summary: We have developed and calibrated TIR instrument to determine its thermophysical properties of asteroid 1999JU3 through thermography. TIR will be able to cover the whole asteroid surface including its dawn-dusk regions, with the spatial resolution less than 1 mrad (pixel resolution). TIR will observe 40 or more images per asteroid rotation every week to trace the rotational and orbital temperature profile.

Reference: [1] Okada T. (2014) *Proc. Intl. CJMT-1 workshop on aster. Sci.* (Oct 2012, MUST, ed: W. Ip), 60-73. [2] Fujiwara A. et al. (2006) *Science* 312, 1330-1334. [3] Ho T.M., et al. (2014) *LPSC* 45, #2601. [4] Okada T. et al. (2014) *LPSC* 45, #1201. [5] Fukuhara T. et al. (2011) *Earth Planet. Space* 63, 1009–1018. [6] Hihara H. et al. (2014) *J. Appl. Remote Sens.* 8, 084987.

Table 1: Characteristic Performance of TIR

Mass	3.28 kg
Power	18W (nominal)
Detector	uncooled bolometer array
Pixels (effective)	328 x 248
FOV	16.7° x 12.7°
IFOV	0.89 mrad (0.051°)
MTF(@nyquist freq.)	0.5
F-number	1.4
Temp. range	233 – 414 K (calibrated)
NETD	< 0.5K
Absolute T resolution	< 5K
A/D Comberter	12 Bit (15 Bit after summed)
Temp. Calibration	Target plate Open/Close